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CEBAF: A SUPERCONDUCTING RADIO FREQUENCY ACCELERATOR FOR NUCLEAR PHYSICS

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) will be a 4-GeV, 200-μA superconducting recirculating linear accelerator to provide CW electron beams to simultaneous nuclear physics experiments in three end stations. Funded by the Department of Energy, CEBAF's purpose is basic research on the nuclear many-body system, its quark substructure, and the strong and electroweak interactions governing this form of matter. At the heart of the accelerator are niobium superconducting accelerating cavities designed at Cornell University and successfully prototyped with industry during the past three years. The cavities consistently exceed CEBAF's performance specifications (gradient $\geq$ 5 MV/m, $Q_0 \geq 2.4 \times 10^9$ at 2 K and 5 MV/m). Construction is under way, and operation is scheduled in 1994.

1. Introduction

Originally foreseen in the early 1960's as promising [1,2,3], superconducting radio frequency (SRF) technology only recently has overcome several technological and practical hurdles. SRF accelerating structures promise low RF losses and high gradients under CW operation. High-quality, intense CW beams can be accelerated without risk of melting the structure and without requiring enormous amounts of input RF power. The instrinsically low RF losses make SRF technology attractive for high-energy electron-positron storage rings and colliders, TeV-scale electron-positron linear colliders, free electron laser drivers, and all types of CW linacs. Fundamental limits for accelerating gradients are ~60 and ~100 MV/m for accelerating cavities made of niobium and Nb_3Sn, respectively. Intense R&D efforts supporting cavity development and accelerator design for all these applications have made significant progress during the past few years.

In 1985, SRF technology was adopted for use in the Continuous Electron Beam Accelerator Facility (CEBAF) [4]. As a 4-GeV, 200-μA, CW electron accelerator for nuclear physics, CEBAF will use 160 m of accelerating structure and become the first large-scale application of the technology. CEBAF is being built in Newport News, Virginia, by the Southeastern Universities Research Association for the U.S. Department of Energy. CEBAF's purpose is to study the structure of the nuclear many-body system, its quark sub-

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in multipass operation, due to multipass beam breakup as a consequence of poor HOM damping.

Table 1

Electron Beam Parameters of Stanford's SCA* [5]

Energy	44 MeV
$\triangle E$	15 keV ($\sim$ 0.03%)
Peak current	up to 500 μA
Emittance	0.02 π mm mr
Normalized	1.7 π mm mr
Energy stability	$\sim 10^{-4}$
Position stability	<0.1 beam size

*Single-pass operation during the 1970s.

In parallel with HEPL's construction, efforts to develop low-beta resonators were initiated at Karlsruhe, Caltech, and Argonne. In 1972, construction of the first superconducting heavy-ion linac using these structures was started at Argonne National Laboratory [7]. It began operation in 1978 as a post-accelerator for Argonne's tandem Van de Graaff. Subsequently several other low-beta superconducting linacs have been built to increase the energy of heavy ions produced by Van de Graaffs [8].

Major R&D efforts have been conducted at Stanford, Karlsruhe, Cornell, CERN, DESY, Wuppertal, Orsay, and KEK to develop improved β=1 superconducting RF structures [9]. Recent improvements have allowed gradients in multicell cavities to exceed 5 MV/m in beam tests, and to achieve up to 10 MV/m in vertical tests. Gradients in single-cell cavities of 20 MV/m are becoming common [10].

Reasons for improved performance are:

- spherical or elliptical cell shape to reduce multipacting (Figure 1),
- improved fabrication and processing methods to minimize defects and surface impurities,
- thermometric mapping to locate hot spots caused by field emission or by defects or dirt on the superconducting surface,
- improved thermal conductivity of niobium to stabilize microscopic defects against driving the cavity normal (Figure 2),
- improvement in welding techniques to avoid spatter and vacuum bubbles in welds,
- beam-pipe couplers to minimize field enhancement, and
- computer codes (e.g., URMEL [11]) to visualize field patterns that may be helpful in the still largely empirical design of couplers.

In addition, titanium or yttrium gettering can remove interstitial oxygen from the niobium, thereby improving the thermal conductivity [12,13]. Either treatment can be applied to

SRF technology economically viable for use in medium-energy and recirculating electron linacs for nuclear physics, for free electron laser drivers, and for high-energy electron-positron storage rings and colliders. For economical application of SRF in very large scale projects, such as TeV-scale linear colliders, improved performance in gradient and Q is necessary.

SRF acceleration has an intrinsic advantage for CW accelerators, since a true CW device is the approach of choice to produce a high-quality continuous beam. Low peak current for a given average current facilitates the achievement of low emittance, and continuously operating RF systems can be controlled more precisely in both phase and amplitude, thereby leading to smaller energy spread and smaller variations of average energy. At high duty factor, particularly in CW operation, copper cavities lose their gradient advantage achievable in short-pulse operation: at a gradient of 3 MV/m power dissipation in excess of 100 kW/m of accelerating stucture not only leads to excessive power demand ($\gtrsim$ 100 MW for GeV-range beams) but also limits achievable gradients below those of superconducting structures, where 5 MV/m can be viewed as a conservative specification. At this gradient, assuming cavity Q-values in the 10^9 range and cryogenic plant efficiencies of $\sim 10^{-3}$, total power dissipation translates into wall plug power of a few kW/m of accelerating structure. Power requirements are thus more realistic than with copper cavities. Further cost optimization can be is accomplished through recirculation, i.e., the repeated passing of the beam through the same accelerating section.

3. CEBAF

On February 13, 1987, construction started on the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, Virginia. The 4-GeV, 200-μA, CW electron accelerator (Figure 3) will have two antiparallel, 400-MeV, superconducting linacs connected by beamlines to allow up to five passes of recirculation [4]. The accelerating structure consists of 1500-MHz, five-cell niobium cavities (Figure 1) [15]. Several prototype cavities have been fabricated by industry, as a result of a technology transfer program initiated in 1985. Tests of the prototypes confirm that the design gradient of 5 MV/m and the design Q_o of 2.4×10^9 at the operating temperature of 2 K are achievable (Figure 4). The production contract for cavities is expected to be placed in spring 1989.

Beam recirculation allows a high energy to be reached with a comparatively modest length and cost of linac. In addition, it is possible to deliver to a few (n) simultaneous experiments beams of different, but correlated, energies. Extraction takes place by removing every nth bunch after the first, second, ..., or final pass. Thus each experiment receives a beam with a frequency that is a fraction ($1/n$) of the fundamental RF frequency. Choice of fundamental RF frequency must account for the fact that the delivered beam can be effectively CW only if its frequency is too high for the detectors to see the individual RF

Recirculating a beam through a linac, however, can produce a transverse instability due to the excitation of HOMs. The recirculated beam and cavities form a feedback loop which can be driven unstable at sufficiently high currents. This multipass beam breakup can severely limit current in a recirculating superconducting linac, due to the intrinsically high Q and long lifetime of the HOMs. Superconducting cavities must be carefully designed to damp HOMs. For the cavity design adopted for CEBAF [15], analytical modeling and numerical simulations indicate that CEBAF's design current is two orders of magnitude below the beam breakup threshold [16] (Figure 5). The two-dimensional numerical simulations are based on realistic lattices and distributions of HOM frequencies. Excellent agreement has been achieved between the analytical code and the simulation.

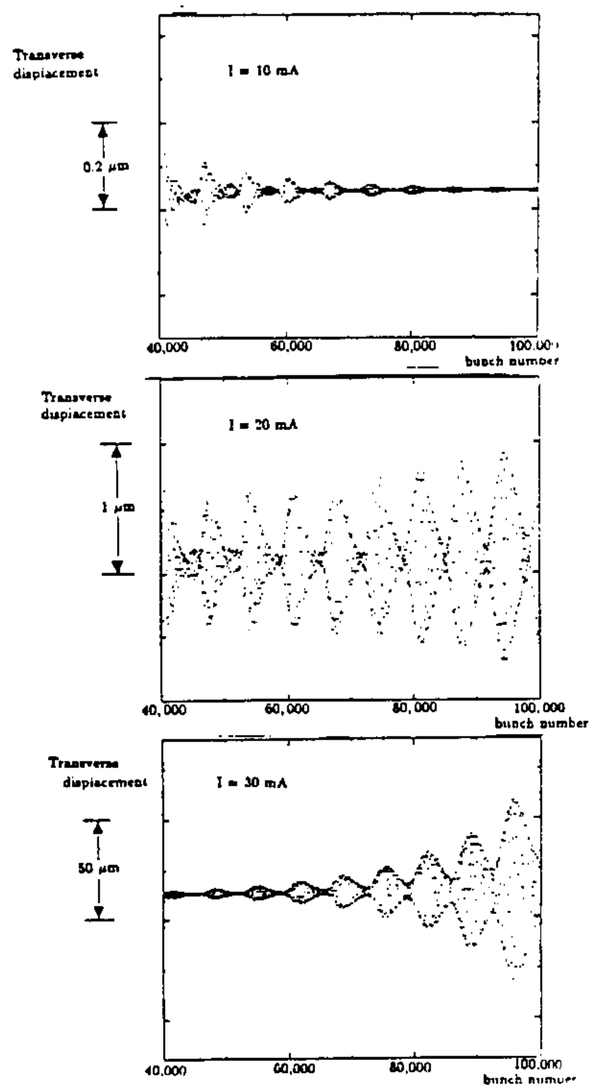

Figure 5 Beam breakup simulations.

The operating temperature was selected on the basis of a cost optimization study. Liquid helium refrigeration systems become more expensive (capital and operating costs) as their design temperature decreases. Yet RF heat losses in the cavities increase exponentially with temperature. For CEBAF the optimum is around 2.0 K.

The RF power system consists of 338 individual RF amplifier chains. Each superconducting cavity is phase-locked to the master drive reference line to within 1°, and the cavity field gradient is regulated to within <1 part in 10^4 by an RF control module. Continuously adjustable, modulo-360° phase shifters are used to generate the individual phase references, and a compensated RF detector is used for level feedback. The close-coupled digital system enhances system accuracy, provides self-calibration, and continuously checks the system for malfunction. Calibration curves, the operating program, and system history are stored in an on-board electrically erasable programmable read only memory (E^2PROM). The RF power is generated by a 5-kW, water-cooled, permanent-magnet-focused klystron. The klystrons are clustered in groups of eight and powered from a common supply.

The beam transport lines connecting the two linac segments are achromatic and isochronous, provide matching in all phase space coordinates, and are designed with adequate bend radii and strong focusing to preserve the high beam quality by minimizing quantum excitation due to synchrotron radiation.

The entire machine is operated in true electron linac mode, i.e., with the particle bunches "riding the crest" of the sinusoidal RF wave shape without longitudinal focusing, relying on the extreme relativistic motion of the electrons. At the nominal injection energy of 45 MeV, total phase slip (with respect to a reference particle moving at $\beta \equiv 1$) is less than 2° through five passes, most of which occurs in the first half of the first pass through the first linac segment.

Table 1 summarizes the CEBAF accelerator parameters.

Table 1
Design Parameter List
CEBAF Superconducting Radio-Frequency CW Linac

Accelerator	
Concept	Superconducting CW recirculating linac
Number of linac segments	2
Number of passes	5
Maximum energy gain per pass	0.8 GeV
Focusing	FODO
Phase advance per cell (pass 1)	120°
Magnetic radii of recirculation arc beamlines	5.1 to 30.6 m

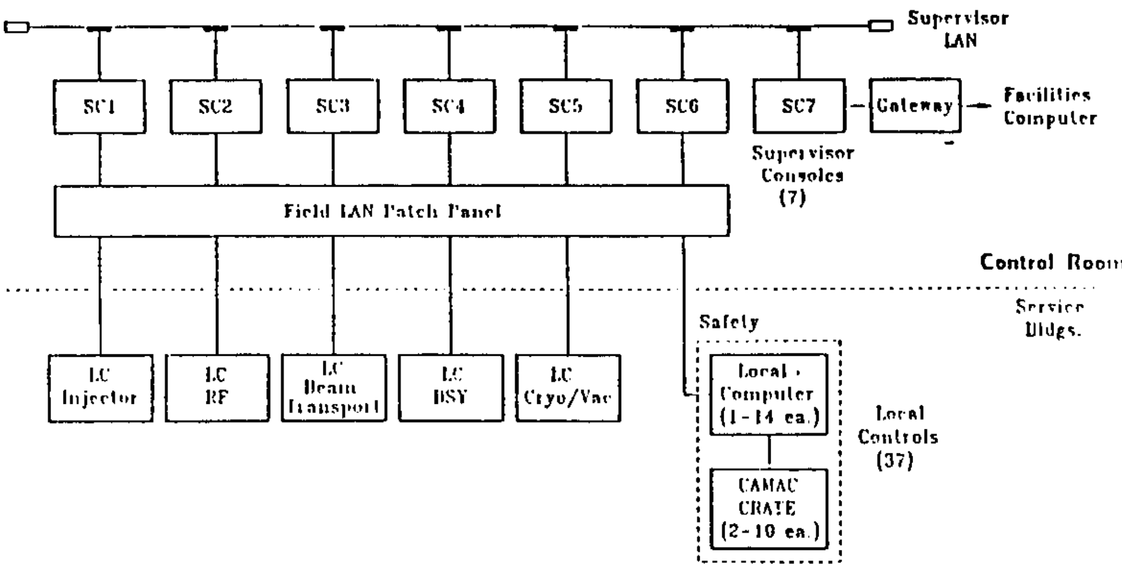

Figure 7 Control system architecture.

<u>Recent Accomplishments and Current Status</u>

The main thrust of construction-related R&D has been to transfer the technology for cavity fabrication to industry and to develop the cryostat system to support the cavity. Test results for single cavities as well as cavity pairs (Figure 4) show that specifications can be met reliably with respect to both gradient and Q values. Experience assembling prototype cryostats has reemphasized how critical proper chemical processing and clean assembly are to maintaining high Q values: low Q values have resulted either from identifiable vacuum accidents or from inappropriate chemical processing. A first prototype cryounit underwent initial RF and cryogenic tests at CEBAF, and tests of a four-cavity subcryomodule were completed in May 1988. In the course of this program a number of needed changes in cryostat design were identified, including increased clearances and other improvements for cavity insertion, improved cavity-support and He vessel-alignment structures, and welded bridging components in the outer vacuum wall. The diameter of the beam pipe connecting two cavities within a pair is being reduced to lower field coupling, and the cavity is being stabilized mechanically to control ponderomotive oscillations. All these changes are viewed as straightforward. A full first cryounit of the new design will be tested in stages this winter, and plans are to test a full eight-cavity cryomodule in late spring 1989.

In addition to the cavity testing and cryostat development, which are now supported by the on-site liquid helium capability of a cryogenics test facility, smaller R&D efforts have focused on magnets, magnet measurement, injector and RF separator development, beam diagnostics and computer modeling. Major elements of the control system are in use in the test lab for cavity and cryostat testing, cryogenics control, RF tests, and injector tests. The injector gun has been thoroughly tested at 100 keV and meets the beam

Table 2
CEBAF Milestones

Start construction	2Q FY 1987 (complete)
Experimental area conceptual design	3Q FY 1987 (complete)
Linac enclosure construction under way	4Q FY 1988
Cryomodule R&D complete	3Q FY 1989
Start front end test (to 25 MeV)	3Q FY 1990
Start CHL operations	1Q FY 1991
Start north linac beam commissioning	3Q FY 1992
Construction project complete	4Q FY 1993
First beam to experiment	2Q FY 1994

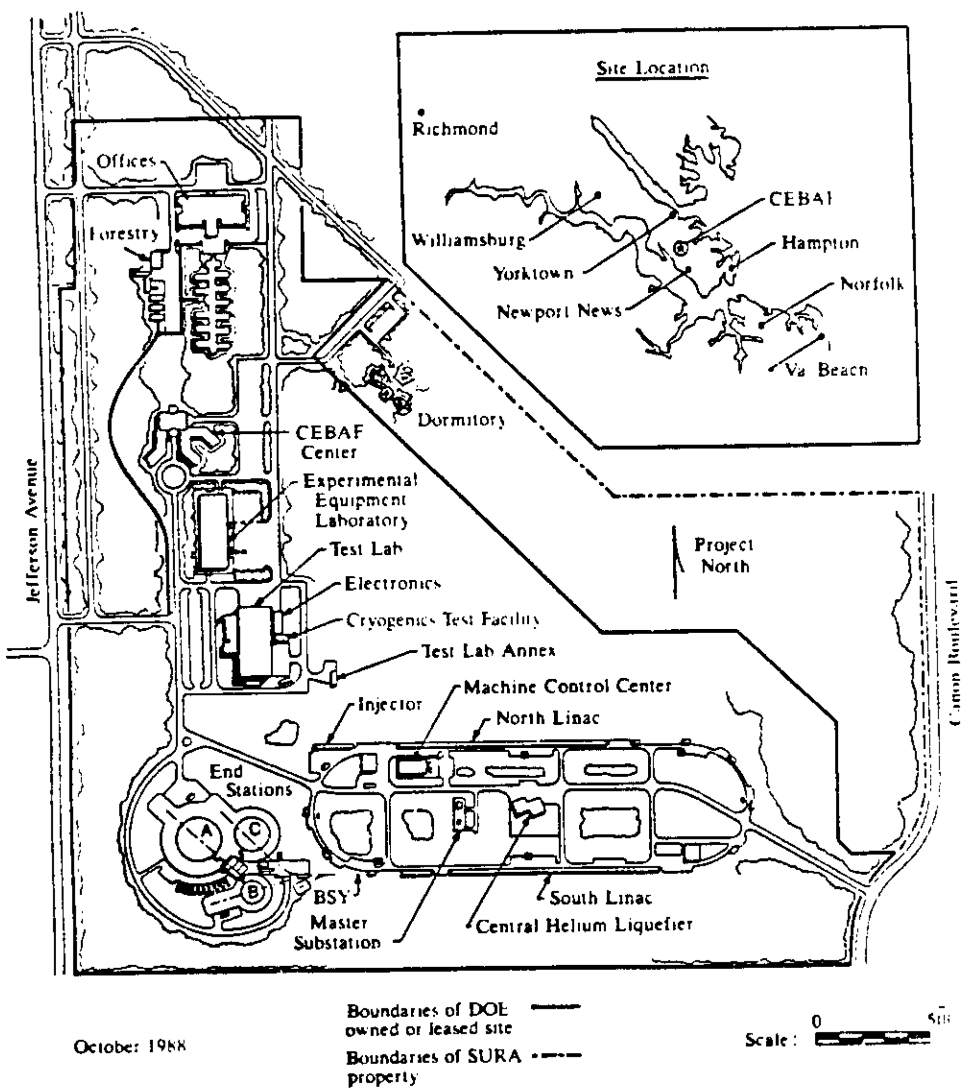

Figure 8 CEBAF's site plan.

superposition with photons emitted by later electrons and by repeated interaction with the electron beam.

RF linacs can provide beams meeting or exceeding the requirements for FELs (Table 3). Output beam quality is most strongly determined by electron gun and preaccelerator performance, although attention to collective effects is essential throughout the whole acceleration process. For FELs with very low macroscopic duty factor, the high gradients achievable with copper cavities may be attractive. For higher duty factors (and therefore higher average beam power) and, in particular, for CW operation, SRF technology allows higher gradients, lower power consumption, and offers the possibility of beam energy recovery. Furthermore, in SRF technology there is less of a penalty associated with low frequencies ($\sim$ a few 10^8 Hz), and therefore substantially lower impedances for HOMs. Thus SRF technology seems to hold a natural advantage for the achievement of very high currents ($\gtrsim$ 1 kA) [21].

Table 3

Beam Requirements for Free Electron Lasers [21]

Energy	$\lesssim$ 1.0 GeV
Normalized emmitance (rms)	$\sim$ 1.0 μm
Peak current	$\gtrsim$ 100 A
Energy spread (rms)	$\lesssim$ 125 keV

Linear Colliders

Synchrotron radiation losses make it highly impractical to produce e^+e^- collisions at very high center-of-mass energy using storage rings. Linear colliders provide an alternative [22]; thus groups at CERN, Cornell, SLAC, KEK, and elsewhere are developing linear-collider approaches for accessing the TeV mass region with a luminosity of 10^{33} cm^{-2} s^{-1} . Two approaches conceived to date rely on SRF technology, either in the linac itself or in a drive linac [23].

Fully superconducting linacs have three advantages over normal conducting linacs: (1) The high cavity Q permits RF power to be supplied slowly, thereby keeping peak power requirements well within current technological capability. (2) Superconducting structures operating at 1000-3000 MHz have acceptable power dissipation and transverse impedance. Tolerances and beam dynamics issues are much less severe than in the 10-to-30-GHz range required for normal conducting linear colliders. (3) The primary issue related to constructability is cost, which imposes minimum requirements on gradient and Q. Gradients in the neighborhood of 30 MV/m—a fivefold to sixfold improvement over industrial capability today—bring the capital costs of a fully superconducting linear collider into the few-billion-dollar range. For CW operation, a simultaneous improvement in cavity Q to

6. A Note on the New Superconductors

In principle, application of the recently discovered superconductors with transition temperatures (T_c) above 90 K could reduce the operating cost of SRF accelerators by permitting a higher temperature to be used, thereby reducing the required refrigerator power. It may also be discovered that the superconductors have other properties which make their application to RF cavities desirable. However, two difficulties make today's high-T_c superconductors impractical: (1) They have a low Q and therefore dissipate a large amount of power which must be removed by the refrigeration system. (2) Their chemical stability is poor. These problems are not intrinsic to high-T_c materials, as studies on carefully prepared crystals show [25]. In the U.S., about a dozen laboratories are focusing on studying the RF properties of high-T_c superconductors.

Initial studies have been made of the RF properties of the new superconductors. Samples made by the Los Alamos National Laboratory and the Bergische Universität (Wuppertal) have been evaluated at Wuppertal in the Federal Republic of Germany [26]. It was found that the material has far greater losses than any metal in the normal-conducting state. In the superconducting state at 77 K, the losses are roughly equivalent to those of room-temperature copper. In contrast, the niobium presently used in superconducting cavities is capable of yielding losses which are 10^5 times smaller than those of copper. At 4 K, the RF resistance of high-T_c materials is about 100 times worse than niobium at 4 K [25].

There is much to be learned about the new superconductors, and their promise for the future is considerable. However, the technological hurdles to overcome today's limitations appear to make unlikely any applications of high-T_c cavities in accelerators in the near term. To develop the new, high-T_c superconductors for RF application will require a major R&D effort focusing on many areas. Examples are increasing the Q, developing high purity and homogeneity, developing methods for depositing thin films with excellent surface properties, adhering the thin film to the substrate, controlling the crystal axis orientation, stabilizing the material, improving the critical current density, and controlling secondary emission (to limit multipacting).

7. Summary

Superconducting RF technology is moving rapidly. A base of experience is building worldwide at accelerator laboratories, at universities, and in industry. CEBAF, under construction in Newport News, Virginia, is the first major accelerator to rely entirely on SRF acceleration. Planned superconducting cavity applications in several accelerators and upgrades have increased the technology's visibility and its pace of advance. Future improvements of SRF performance, from today's gradients of $\gtrsim 5$ MV/m and Q's of $\sim 2 \times 10^9$ to gradients of ~ 20 MV/m and Q's of approaching 10^{10} can be foreseen. Future applications in storage rings, free electron lasers, and TeV-scale colliders can be envisioned.

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26. M. Hagen *et al.*, "Observation of RF Superconductivity in $Y_1Ba_2Cu_3O_{9-\delta}$ at 3 GHz," April 1987, Preprint Bergische Universität Gesamthochschule Wuppertal, WVB 87-12.